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System Analysis Approach to Deriving Design Criteria (Loads) for Space Shuttle and Its Payloads

Volume I — General Statement of Approach

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and Space Administration

Scientific and Technical
Information Branch

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TECHNICAL PAPER

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INTRODUCTION

Mission operational and performance requirements coupled with low-cost drivers dictate an optimized design that has a quantified success probability. The ability to achieve an optimized design and quantify the success probability in a variable and complex operational environment coupled with complex configurations and highly interactive design disciplines are major problems facing engineering. The answers do not only depend upon the independent analysis conducted by the various disciplines but also upon how a systems analysis including parameter variations is treated; what use is made of safety factors; test philosophy used; test factors such as proof factor, static load test factor, qualification versus acceptance test factor, and dynamic test factor; and the accuracy of available analyses and testing tools. Programs prior to Space Shuttle, in general, required only a limited amount of these coupled system analyses. Basic trajectories could be run using mean winds, three-dimensional models, and idealized control with no coupling for developing loads. The vehicle configurations were generally axisymmetric; hence detailed coupled analysis was not required. The same could be said for thermal and control. The interdiscipline communications problem was minimized, since there was only a limited requirement for it, and this could be handled at the project level.

Space Shuttle is a prime example of the other side of the coin exemplifying this complexity. The structure is multibody, connected by joints, with both static and dynamic asymmetry. Aerodynamic interaction forces, in addition to the structural asymmetries, closely coupled control, loads, thermal, and performance, forcing detailed system trades to achieve a workable design. Shuttle payloads have the same problem in that they must withstand launch, orbit, reentry, and landing environments. Either launch or landing usually becomes the design driver instead of the operational requirements.

The categories of interactive problems mean the loads engineers and the project must conduct many special analyses. Some of the analyses may be restricted to the preliminary design phase; however, in general, they must continue through verification. A general categorization of these analyses is load-alleviation trades.

The implementation of load-alleviation techniques should be constantly pursued in order to reduce weight and eliminate costly redesign and schedule impacts. Any approach which becomes a strong candidate for alleviating or eliminating loads must be assessed by all other disciplines which may be affected by the proposed change to determine its system validity. A very close working relationship between the loads community and the other organizations is required to determine if the benefits from load reductions outweigh the detrimental effects in other areas. Some examples of load alleviation or preventive measures which can be taken to optimize design or eliminate redesigns are provided below:

a) Engine Ignition Sequence – Options should be built into the avionics network to accommodate engine ignition and engine shutdown stagger time/lag time to reduce liftoff and engine cutoff loads. The optimum sequence can be determined once a good model of the vehicle and launch pad have been developed. A verification of this sequence can be obtained from an on-pad static firing. The optimum sequence will prohibit or minimize forcing functions and modal tuning.

b) Controlled Thrust Rise Rate – The thrust rise rate should be kept as low as possible to reduce vehicle response at liftoff. The lower rise rate will also minimize ignition overpressure. Also, with a multiple engine configuration, all efforts should be made by the engine personnel to minimize the unsymmetrical engine to engine thrust rise or decay.

c) Launch Pad Design – The launch pad designers should make every attempt to design and build the launch pad whereby all vehicle/pad support locations have equal stiffness. This reduces or eliminates the possibility of differential point loads due to stiffness unsymmetry on flight structure during the on-pad ignition or liftoff abort event.

d) Material Selections – Certain composite materials are advantageous because of their light weight. Some of these materials have high strength capability and could replace the steel cases in large solid motor design. Although many composites will meet the internal pressure and loads requirements, the lower structural flexibility could cause loads problems in the other elements of the total configuration. To avoid these problems, the loads analysts must perform detailed loads studies, particularly for the on-pad and lift-off events, to determine minimum stiffness requirements, both longitudinally and laterally, which can be tolerated with regard to the resulting loads on the other elements. These stiffness requirements must be defined to support the conceptual design of the motor case. A knowledge of the on-pad deflections (lateral in particular) early in the program can prevent schedule impacts in umbilical and service platform design/modifications.

e) Interface Attach Structure Preload – The temperature environment changes considerably in liquid propellant containers from the empty to the loaded conditions. The deflections caused by the cryogenic condition result in very high loads at the interface attach structure which has to be absorbed in the ring frames and bulkhead or skin structure and creates a buckling stability problem. To accommodate this load, additional weight is required. To reduce the magnitude and offset a portion of this cryo tension load, a precompression load can be effected before the vehicle is loaded. In addition to alleviating the on-pad loads, the strut tension loads during the liftoff twang is also reduced.

f) Inflight Load Alleviation – Several approaches to load alleviations are used for the maximum dynamic pressure (max q) and other flight regimes, such as trajectory biasing, engine throttling, thrust profile tailoring (solids), control system logic, and others. Any alleviation associated with engine thrust profiles must be defined very early in liquid propellant engines. Thrust profile tailoring for solids, however, can be implemented somewhat later since a change in propellant grain shaping within certain bounds can produce the desired thrust profiles. Control system logic can be changed very late in the program. Trajectory biasing can be accomplished as late as the day of launch, based on measured environments.

Most all of the above load alleviations have been implemented on the Shuttle vehicle. The changes in the approaches alluded to above have reduced cost, weight, and schedule impacts. In the assessment of any new configuration or the performance enhancements of existing configurations, loads exceedances will usually occur because the environment, thrust, or structural dynamics model is in the process of being updated long after the basic design has been completed. However, these load exceedances can usually be eliminated by innovative ideas of the loads analysts in finding ways to alleviate the loads without detrimental effects to other systems.

The objective that should be pursued in these studies and system loads analysis would be to achieve a 3-sigma probability for structural integrity such that the factors between external loads, internal loads (stress), and lifetime do not stack but are weighted together in the structural criteria and verification.

This report will deal with these issues. In addition, examples of loads analysis, etc., for Space Shuttle, its payloads, subsystems, and elements will be presented.

VOLUME 1

OVERALL CONSIDERATIONS FOR LOADS

SECTION I. GENERAL APPROACH

Generation of aerospace vehicle design loads can usually be considered as existing in four phases: concept formulation, preliminary design, detailed design, and design verification or certification. In general, each of these phases cannot be thought of as one load cycle but each encompasses more than one major load cycle with several minor or partial load cycles. One usually thinks of load cycles from the air frame or total systems standpoint. This is not correct, however, since a subsystem or component has a cycle that uses as a portion of its input environment the accelerations, etc., from overall loads analysis. Many times, the complexities of some subsystems dictate a requirement for separate independent cycles. For example, consider the Space Shuttle Main Engine. This subsystem generates its own design environment; namely, acoustics, pressures, and thermal. Thus, it is basically insensitive to anything transmitted from the Shuttle other than the steady-state g forces and can be treated with its own induced environments and load cycles. In all cases, a major problem occurs because of the long time required for a design cycle. Consider that environments and models must be defined one to two years prior to the final loads dump and are consequently based on incorrect configurations. Consequently, design changes are not reflected in load results until a long time after design implementation. If this design change affects models or environments drastically, then the assessment comes too late. In fact, this very problem precludes, in general, optimized structural design. Figure 1 depicts a typical sequence for a launch vehicle and illustrates the problem.

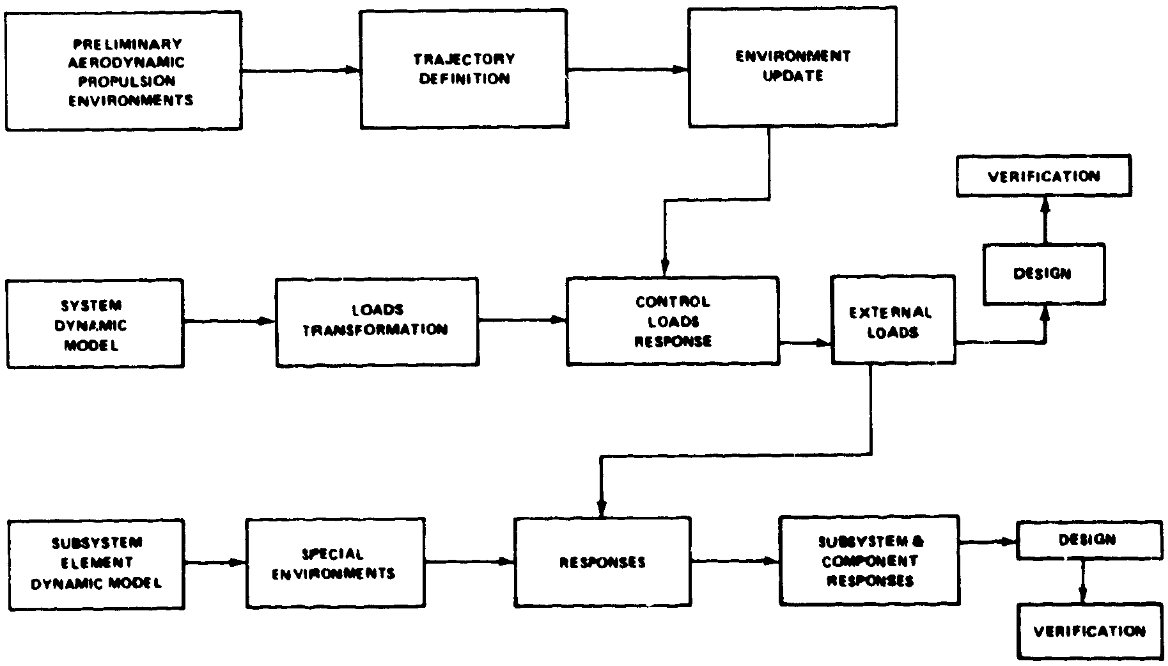


Figure 1. Typical load cycle flow.

Here again, the loads analysts must be involved in the design of suppression systems, isolation systems, etc., in order to make designs and environments compatible. In dealing with loads, the analysts must apply linear and nonlinear time response techniques, frequency response techniques, modal analysis techniques, and statistical techniques. It is clear then that many problems exist in the loads world from long analysis cycle time, configuration updates, etc., and that the loads analyst must not only be an expert in loads calculations but must also concern himself with design, environments, etc.

For there to be any hope in getting through the maze requires an orderly, well thought out approach. Once a configuration has been selected (which also involves the loads engineer), this approach starts with design philosophy definition, a sensitivity analysis, environment definition, models and simulation requirements and definition, analysis approach selection (by design phase), loads combination approach definition, and basic operations approach definition. Each of these areas will be discussed in the following paragraphs. The discussion will first go through a general discussion. A final section will deal with special problems associated with payloads because of their importance to Shuttle usage.

A. Sensitivity Analysis of Generic Configuration

The first step that any project and the load engineer should attack is determining the vehicle's basic sensitivity. Many disciplines are involved. Structural control interaction has received and is receiving much attention (References 1-20). Most of these efforts have attacked the basic stability question with some emphasis on reducing angle of attack, thus rigid body loads. Additional efforts have been expended on reducing elastic body response to gust loads and active flutter control, particularly for aircraft ride control. The authors treated some of these areas in References 21 and 22. Figure 2, repeated from References 2-4, illustrates these key issues envisioned early in Space Shuttle concepts and design studies.

Here, if the objective of maximum payload to orbit is met in conjunction with reduced sensitivity to environment and variable payloads and missions, an integrated system analysis is required. As a result of these analyses (to be discussed in a later section) or trade studies for Shuttle and its payload, it is apparent that the integrated approach must be broadened for future systems. A good indication of these trends is the work accomplished in the aeronautics industry and in government research in the areas of controlled configured vehicles, aeroelastic tailoring, and active flutter suppression. As the space program moves forward into the Shuttle applications area, future high-lift transportation systems, large space structures, and interplanetary travel dictate additional efforts and technology in system design concepts and tools.

In most of the past efforts, structural dynamics has been secondary. Future concepts reverse this role with structural dynamics becoming primary. This means, in general, that design has moved from one dominated by strength to one that is stiffness driven. Stiffness driven designs, in general, require integrated analysis approaches such as control configured techniques, etc. Regardless of the resulting complexities, all future configurations point to a need for drastic change in design approaches to meet the performance, cost, risks, and schedule constraints. The starting place for building a new approach is a basic sensitivity analysis.

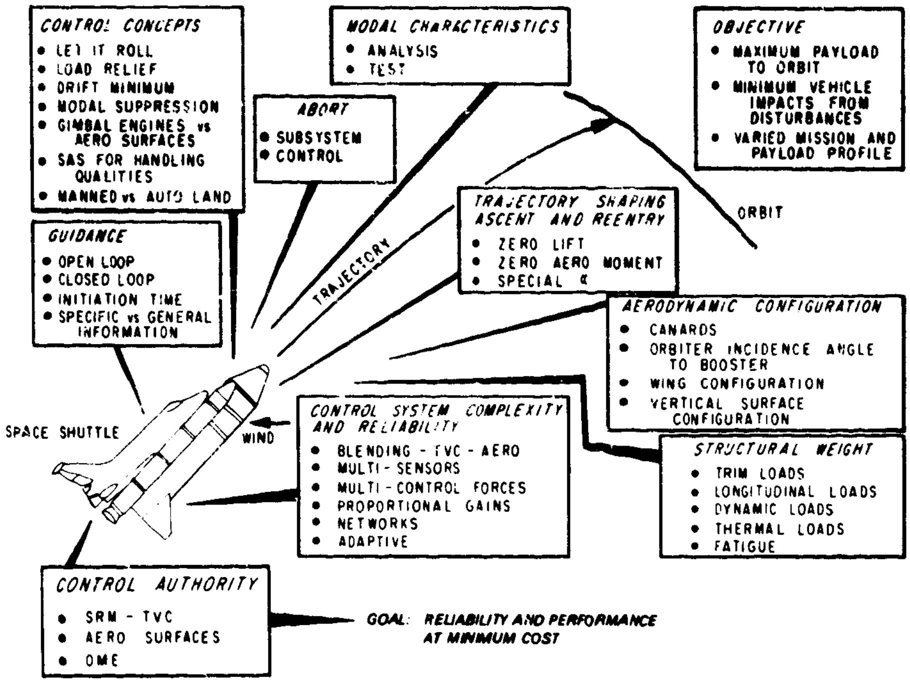
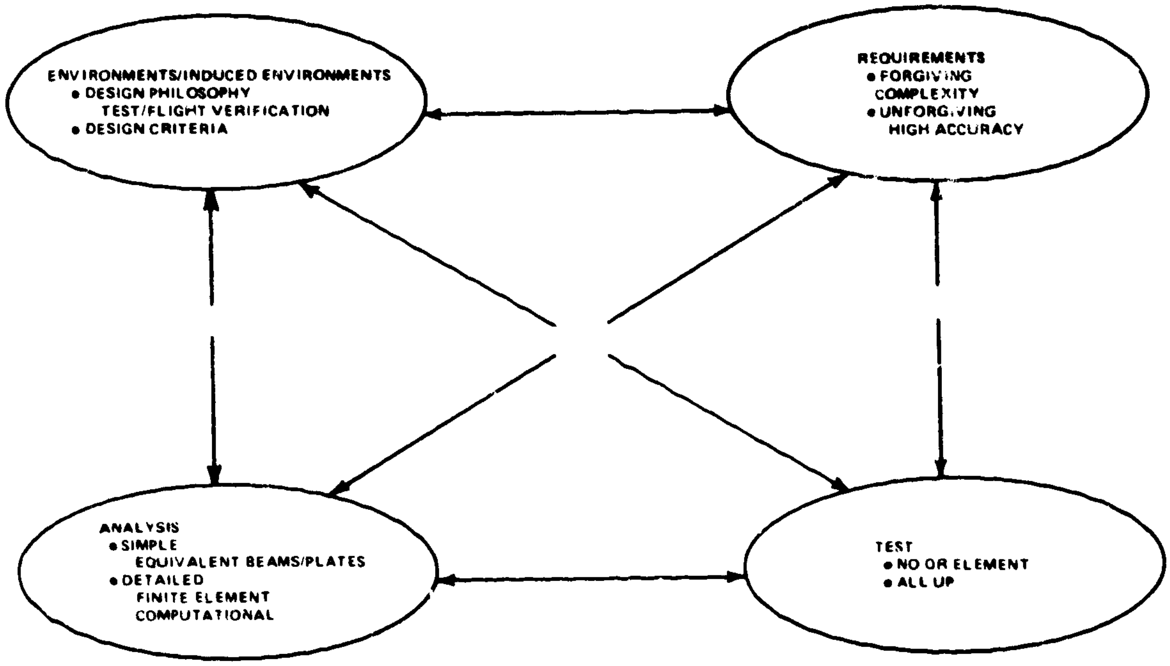


Figure 2. Key Shuttle issues.

The sensitivity analysis must cut across the interacting disciplines, mission requirements, and generic configurations. The analysis should start with very simplified models containing only first-order effects and generally require only rigid body simulation for inflight loads. The next step, the inclusion of elastic body effects, should be done with very simple models and linear analysis. These studies will bracket problems and determine areas to penetrate in design. These early system sensitivity analyses cannot be emphasized enough. They are the foundation for design philosophy, design approaches, resources, etc. With a good basic sensitivity analysis at hand, the program must move to develop a design philosophy and criteria approach again from a systems viewpoint and not just loads. In the early days of the Space Shuttle, a series of sensitivity studies were made (References 2, 3, 4, 5, 6, and 23). Initially, the solid rocket boosters were designed without control authority. These sensitivity studies showed a clear requirement for this control authority or they would suffer greatly reduced controllability and large payload losses due to path deviation and higher loads. These same studies delineated an optimum mixing logic for control between the main engines and the solids. There were several preliminary special contracts in the load alleviation and aeroelastic response areas (References 24 and 25) that showed the potential for significant payload gains through reduction of aerodynamic induced external loads. These same studies (Reference 26) showed small effects due to aeroelastic gust loads with insignificant gains using modal suppression. The advantage of monthly mean wind biasing was illustrated at this time. Early studies demonstrated the requirement for using a modified 6-degree-of-freedom trajectory in shaping trajectories for use in loads and control instead of the 2 degrees-of-freedom used in Saturn/Apollo. These sensitivity studies became the cornerstone for control logic, load analysis techniques, and design changes.

B. Establishing A Design Philosophy

The next step the loads specialist gets involved with is helping establish a design philosophy. This task begins with the mission requirements and objectives. A single mission structure can be designed quite differently from one that must withstand 100 missions. Operation time is also important. A space structure designated to stay in space many years has different considerations from one that has a limited (seconds or minutes) lifetime. A requirement for test verification also influences the designs. Figure 3 illustrates the interactions involved in determining the design philosophy as well as criteria, test, requirements, and analysis.



*TRADE DIFFERENT FOR EACH FLIGHT PHASE

- LAUNCH
- OPERATIONS (ON ORBIT)
- RETURN (LANDING)

Figure 3. Systems trades.

Early sensitivity analyses are mandatory prerequisites for the loads specialist in order to properly accomplish, in an efficient manner, the design loads tasks he faces. Also, a smaller based sensitivity analysis must be continued up until launch to serve as a basis for control logic and trajectory shaping logic changes.

The initial philosophy statement starts with a generalized statement. The space vehicle design shall have a 95 percent probability of success for the family of missions specified in the mission requirements document in terms of performance, reliability, etc. These requirements are to be accomplished within the cost and schedule constraints by making maximum use of control and aeroelastic tailoring, weight-saving materials, etc., through an integrated system design approach. The system will be designed for safe mission abort and have fail-operation/fail-safe component design. This philosophy will be met using a systems approach that includes system parameter variations such as environments, thrust, and structural dynamics. Using the design philosophy stated in general terms as a guide, a series of sub-philosophies or objectives is then derived. These objectives strongly affect the design even though they cannot be absolutely defined because of the many factors involved. Some typical ones are (Reference 27-33):

1. Weight

a. Ferry loads should not exceed operations and nonflight or non-operations loads, and should be accommodated or borne with ground equipment designs.

b. Weight should be minimized using any available techniques.

2. Simplicity

a. The structural design should emphasize simplicity. Exotic load paths create special problems and should be avoided.

b. Avoid dynamic coupling of several independent elements as a design approach.

3. Cost

The structure should be designed to minimize total cost over mission lifetime.

4. Repair

Structural capability should not be degraded by repair nor should allowance be included in design loads to account for potential repair degradations.

5. Compatibility of Requirements

To faciliate the development of compatible structure, the following requirements or constraints should be established as early as possible in the design process:

a. Safety.

b. Reusability.

c. Life.

d. Turnaround time.

e. Risk/reliability.

f. Mission duration.

g. Mission abort.

h. Safety factors.

It is not the purpose of this paper to discuss these individually, but to point out their importance in loads and systems analysis. For example, using the trades exemplified in Table 1, the project can adopt the philosophy of simplicity for control design. This choice, in general, automatically leads to the requirement for accurate dynamic data, thus a requirement for all-up dynamic testing. Simplicity or elimination of static testing leads to the incorporation of larger safety factors, hence higher design loads and more structural weight. Obviously, part of the decision in these trades involves the accuracy with which one can calculate the external loads. Other factors inherent in this design philosophy chart (Figure 3) and the ensuing trades, not shown explicitly, merit some discussion. The selection of the material for a given structure should be made based on dynamic criteria; i.e., is high-elongation, energy-absorbing, forgiving-type material required, or is high-strength, fracture-tough material better? Just as important are the criteria for use of selected induced-response loads for increasing structural stability, e.g., venting controlled for shell stability, or early thermal concerns, bondline stresses, and dynamic effects. Here, these can be balanced in an optimum way to reduce loads and increase performance if all the appropriate disciplines work together properly.

Mentioned in the introduction were safety factors, etc. All test factors should be made compatible and include proof factors, dynamic test factors, and static load test factors. In case of component qualification and acceptance, test factors should also be included.

One additional point is paramount in these areas. The loads engineer who combines loads from the various sources must have an intimate knowledge of specific stress application of the load, e.g., acoustic panel response load versus panel interface g-load factor.

Loads and loads analysis/test approaches are fundamental in the design philosophy; hence, the program cost and schedules. The corollary is also key: The design philosophy chosen drives the loads analysis/test approach, cost, and schedules. The conclusion is obvious: loads specialists must be systems oriented and be in an interactive mode with program/project offices and other technical disciplines helping shape the design philosophy which, in the final essence, drives the load analysis approaches he uses.

C. Definition of Environments

The next area of concern is the environment definitions.

External loads are only as accurate as the definition and statistical quantification of the external environments. This means that the loads specialists must be very active in the setting of requirements for and the definition of environments. This process starts in the early program conception stages and stays active through flight demonstrations. The definition of environmental requirements starts with an analysis of the mission profile Figure 4 depicts the Shuttle profile starting with the vehicle on the mobile launch pad subject to transportation-induced loads and ground-wind loads and ends with the landing-induced loads. Illustrated in between are the max q environments, staging, solid rocket motor recovery, tank disposal, and Orbiter reentry.

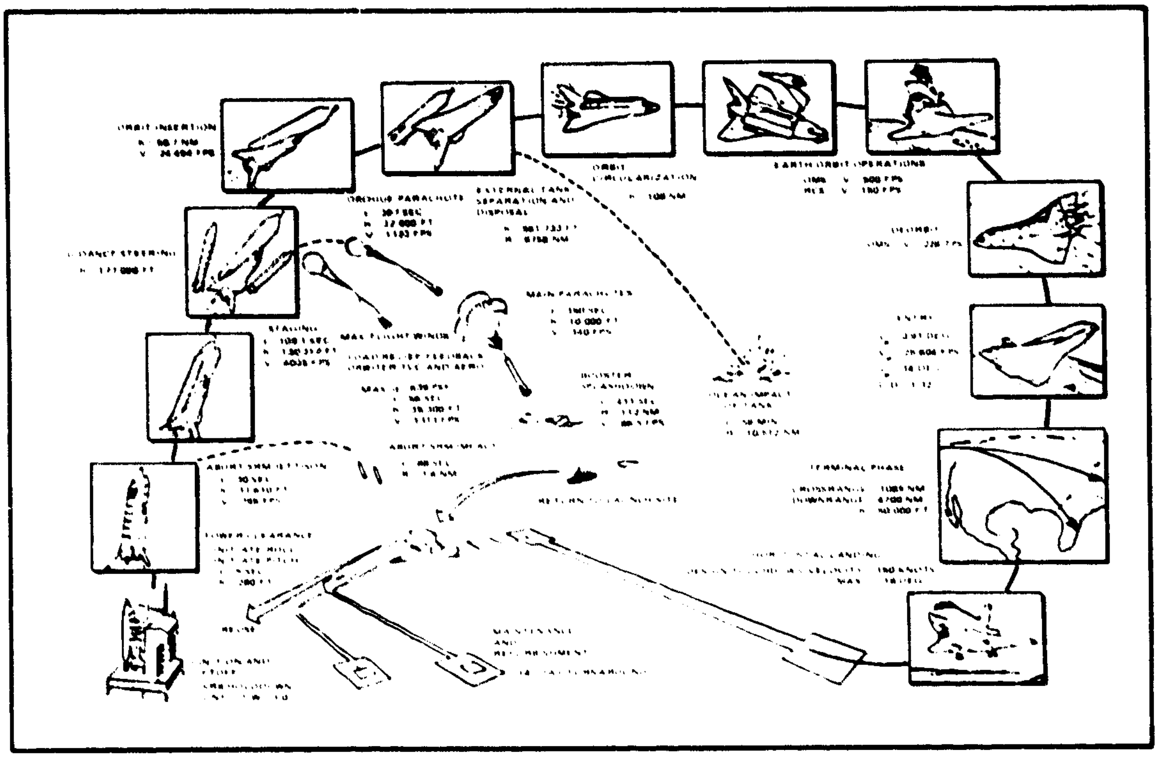


Figure 4. Space shuttle mission profile.

The Space Shuttle, in the early conception stages, attacked this problem through a series of technology committees organized and chaired by the NASA Office of Advanced Space Technology. The committee concerned with loads was Dynamics and Aeroelasticity. Committee membership consisted of individuals from LaRC, MSFC, etc. This group, through technology planning, developed much of the preliminary data and uncovered many potential problems.

Certain vehicle components, as well as payload experiments, are very susceptible to combined low-frequency and acoustically induced loads. MSFC proposed a 6.4% Shuttle ignition acoustic model using small solids and a hot-gas main engine system with the launch platform simulated through this technology committee. The program was approved and the model developed. Figure 5 shows the setup.

As a result of these tests, it was concluded that the acoustic levels were too high and that a noise-suppression system was required. As part of this study, solid and liquid engine parameters such as thrust rise rate were studied. As a result, a water noise-suppression system was designed and verified for the Shuttle launch pad. Figure 6 depicts one of the configurations tested.

In the early design phases of the Shuttle design, the Titan program discovered a payload loads problem at liftoff. The source of this problem was believed to be ignition overpressure due to the launch facility design and the thrust rise rate. As a consequence, Shuttle

Figure 5. 6.4% Acoustic model test facility.

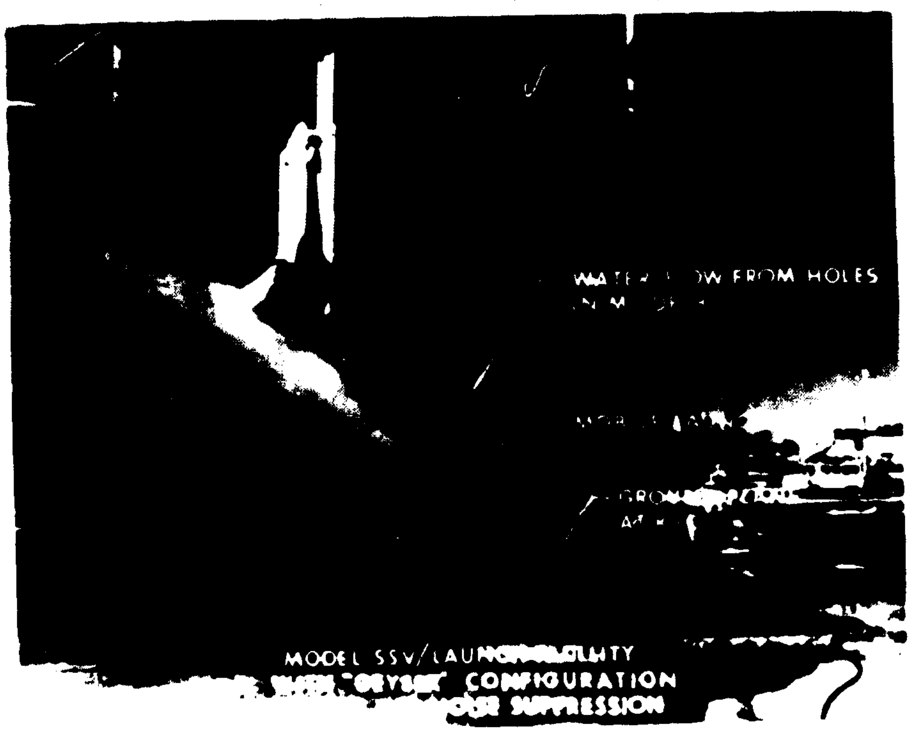


Figure 6. Model SSV/launch facility with "geyser" configuration for liftoff noise suppression.

management started an investigation of the potential of ignition-overpressure induced loads. The 6.4% model was used to define this environment which turned out to be significant for Shuttle liftoff loads. This experience points out the need for, and the requirement to do, a thorough research of prior programs and the critical environments from a loads standpoint.

In this area, the propulsion system characteristics are a key element. Shuttle is sensitive to thrust ignition transients at liftoff as well as thrust oscillations throughout burn. The description of the thrust mismatch for the Solid Rocket Boosters is of primary importance. Initially, the Titan and other programs were used as a source. The SRM demonstration and qualification program was used as a source for the final environments. Special instrumentation was added to acquire these data. All propulsion test programs are good sources for environmental data and should be piggybacked to reduce cost.

During maximum dynamic pressure flight regimes, two environments are key to loads: winds and aerodynamics. MSFC, for many years, has been the source for winds and atmospheric environments (References 34-36). The data exists as individual wind profiles and as statistical wind combination as mean winds, shear envelopes, gusts, and the synthetic wind profiles. These data are under constant revision. In general, the data can be conditioned or modeled as required to fit special requirements. This means a close working relationship between the loads, control, performance and atmospheric environment groups to ensure correct definitions. The Space Shuttle is sensitive to changes in both wind direction and wind speed with altitude. As a result, the vector synthetic wind profile was developed. All future programs should achieve this type of interdiscipline interaction to ensure proper environment definitions.

The same approach must be taken for aerodynamics and aeroelastic environments definition. A progressive test program must be defined that starts with the basic configuration, progresses to adequate incorporation of aerodynamic protuberances, and ends with aeroelastic test to ensure that the system is flutter free. Experiences with the definition of Space Shuttle aerodynamics uncovered several key issues in the aerodynamic definition area. These were:

1. How does one apply tolerances on pressure distributions for use in loads analysis?

2. How does one ensure accurate data from wind-tunnel tests because of sting effects, shock reflections, tunnel blockage, and model imperfections?

3. What were power-on effects, and how does one correct data obtained without power for these effects?

4. What is the appropriate way to apportion body-to-body tolerance effects on interface forces?

5. How does one solve the problem of balancing integrated pressure distribution forces and moments with total forces and moments obtained in balance tests?

6. How does one acquire accurate definition of protuberance forces and effects on small scale models?

7. What is the best way of accounting for aerodynamic variations, particularly body-to-body (ET, SRB, Orbiter)?

8. Is it possible to improve or validate aerodynamics through use of flight data?

It is not the purpose of this paper to discuss in detail the aerodynamic data definition; however, it is clear that this definition and the coordination with loads personnel is very important. Some additional comments will be made in this area under the loads-results discussion.

All environments must follow the same approach illustrated here. Definition of the environment is paramount to adequate loads definition. The loads analyst is a key member in planning and placing requirements on the environmentalists.

The Space Shuttle, with its reusable concept and large aerodynamic surfaces as well as skin panels, is susceptible to all types of aeroelastic responses. These considerations require the load analyst's involvement in this area also. The same concerns are applicable to any space vehicle that must undergo atmospheric environments directly. Obviously, the same class of problems can exist in orbiting space vehicles in the form of gravity gradient, solar pressure, and magnetic torques. The general class of problems for atmosphere is flutter of wing, tail, appendages, skin, protuberances, buffet, vortex shedding of protuberances, divergence, aero surface stall, etc., and gust loads. Not only must the limit load be determined but also the cyclic load for fatigue on lifetime predictions. The aircraft industry has documented proved techniques including wind-tunnel testing for determining environments, flutter limits, etc., and therefore these are not discussed in depth. The load engineer must be conversant with these problems, techniques, and published literature so that he can ensure proper coverage.

In summary, definition of the environments is critical for proper design. The load engineers are key in their determination as they work with the environmentalists. These activities must cover all phases of flight from liftoff through ascent, orbit, reentry, and landing.

D. Definition of Models/Simulations

The choice of models and simulation approaches is present at all stages of the analysis cycle and design. Results are only as good as the models de..ned for their generation. Because of schedules and costs, the tendency is to simplify the approaches as much as possible. Simplification can be accomplished only if load-parameter sensitivity has been established. It should be pointed out also that this sensitivity must be under reevaluation with the advent of new environments, design changes, or dynamic test results. One must keep in the forefront at all times the fact that models are just that: models, and they can predict only what has been included in their development. Even with high-powered finite element models, one cannot cover everything. If the attempt is made to be all inclusive in modeling, computer cost and run time are prohibitive.

As was pointed out earlier, loads models must incorporate all disciplines that have first- and second-order effects on loads. For example, the oscillatory loads and thus the lifetime of the LOX posts in the Shuttle Main Engine injector head are dependent on the thermal environment in two ways. The posts have extreme temperature gradients across the tube wall, being 1800°R on the outside and cryogenic on the inside, which change its elastic properties. In addition, the tube is in compression on one side and tension on the other, changing the boundary conditions where the post is threaded into the face plate. Both conditions alter mode shapes and frequencies. This means that the dynamic loads model must include a detailed thermal model. Looking at the Shuttle system and the results of preliminary sensitivity analysis, it is clear that loads analysis must include fairly detailed models of the control system; aerodynamics including body-to-body forces and moments; trajectories; structural dynamics; and atmospheric wind-speed shear and gust. Figure 7 illustrates this simulation built up from the individual models. These models and the resulting simulation require a time-dependent solution with detailed time varying coefficients. A more detailed discussion of these models and simulation will be presented in the section on Shuttle loads.

SYSTEMS DYNAMIC LABORATORY ENVIRONMENTS AND LOADS CYCLE

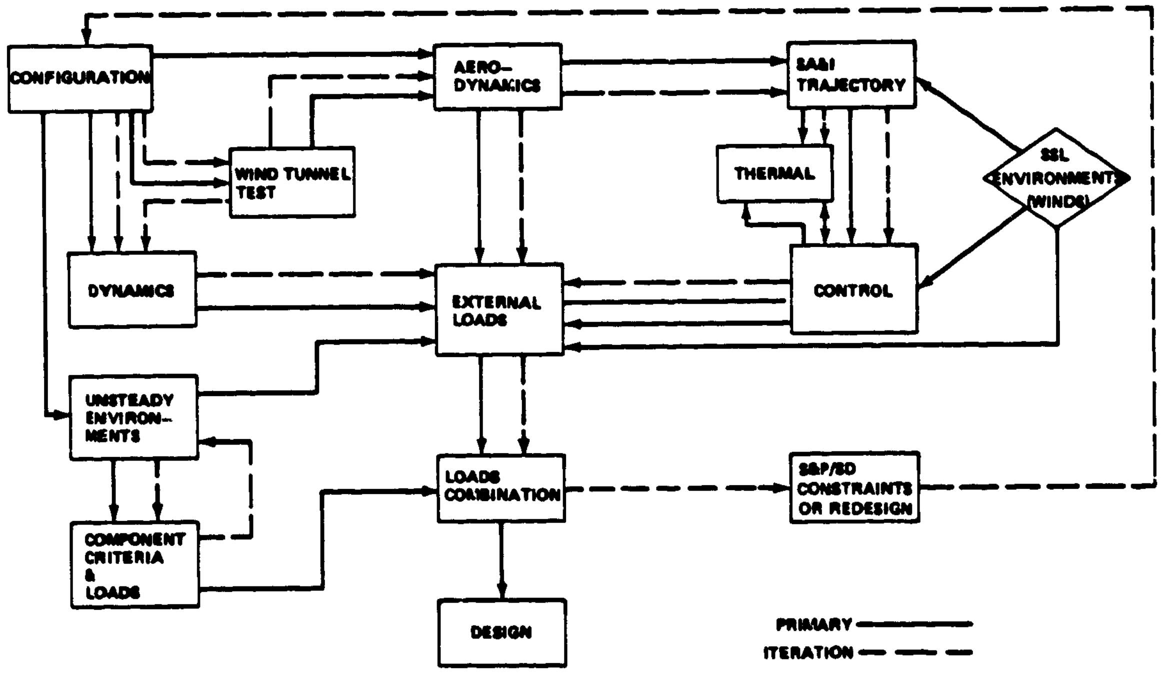


Figure 7. Environments and loads cycle.

Criteria based on the sensitivity analysis must be developed for determining models and simulation requirements. The following guidelines help arrive at these criteria:

1. Structural Dynamics

a. Ratio of environment (forcing function) frequency to structural dyanmic frequency.

b. Ratio of static loads/rigid body loads to structural dynamic loads.

c. Sensitivity of loads to local pressure distributors.

d. Control system response characteristics compared to structural dynamics response characteristics.

e. Load paths.

f. Can air frame (basic structure) be treated without component definition other than mass?

g. How important is time sequencing on loads? liftoff? separation?

h. Is a time-response analysis necessary (nonlinear) or can PSD or static analysis be used?

2. Thermal

a. Does thermal affect dynamics or can it be added in as induced stress?

b. Do thermal constraints affect trajectory shaping, and thus, loads?

c. Does thermal affect on-pad loads from warm to cryo conditions?

3. Environments

a. Vehicle frequency response characteristics.

b. Sensitivity of loads to basic environment characteristics.

c. Design philosophy.

4. Induced Environments

a. Sensitivity of loads to variations and unknowns.

b. Vehicle frequency response characteristics.

c. Design philosophy.

d. Percent of loads due to induced environments.

5. Control

a. Can gust loads be treated separately or must they be considered simultaneously and time consistently with rigid body?

b. Loads sensitivity to control parameters.

c. Is load relief a requirement? How much dependency is placed on control to reduce weight, etc.?

Obviously, the details required in the models will be a function of design status. Early and preliminary design phases usually can be accomplished with very simple models, while final design and verification tend toward a requirement for very detailed models.

In summary, the selection of the model determines the validity of design loads. Models must be selected in terms of the many factors discussed. Load engineers by nature must be very versatile people.

E. Selection of Analysis Approach

The selection of the analysis approach is dependent upon the considerations identified in the previous section and other influences. In fact, the selection of the types of models must be made in conjunction with an analysis approach. This selection depends on the many factors discussed previously as well as the type load being sought. For example, if a linear analysis can be used, but there is a requirement for detailed dynamics (large number of modes) and aerodynamics, then one can employ the frequency-domain analysis much more efficiently than conducting time-domain analysis. Conversely, if nonlinear, time-varying coefficients in conjunction with detailed dynamics is required, then time or transient analysis must be used. The Shuttle liftoff loads analysis, to be discussed in more detail in a later section, requires multi-constraint, nonlinear time analysis using all modes (approximately 130) below 20 Hz. In this case, computer time and simulation complexity must be sacrificed for accuracy and completeness. Not only must the analysis approach for the loads themselves be chosen but the modal analysis approach is also a fundamental part of this selection. For payload analysis where the launch vehicle does not change, but the payload is variable, one can choose to modal-couple the launch vehicle with the payload to obtain modes for the coupled system and then run a conventional transient-loads analysis. Alternately, the payload can be coupled to the launch vehicle in the transient-loads analysis (coupled base motion approach). Selecting the analysis approach requires selection of the simulation approach, statistical analysis approach, methods for forming the describing equations, criteria to use in selection, and interdisciplinary considerations.

1. Simulations of Describing Equations

Hybrid computers are very effective tools for loads analysis, particularly when a six-degree-of-freedom, rigid-body trajectory, control simulation is adequate or only a limited number of modes are required (References 1, 7, 9, 10, 11, 12, 13, 16, 17, and 37). Nonlinearities are easily simulated on these computers. Hybrid computers are very useful in Monte Carlo-type statistical analysis because of their high-speed capability.

2. Statistical Analysis

So far, the discussion has dealt only with the method of simulating the describing equations for generating the loads. Just as important is the statistical approach chosen for quantifying the design probability. One method used extensively for approximating a 3-sigma response of a system under 3-sigma parameter variations is the A-factor approach. This approach determines a time-consistent, 3-sigma response run using a weighted variation on each parameter. The weight for each parameter variation is determined by first running each 3-sigma parameter variation individually producing a delta response. The delta responses are then RSS'd to obtain a 3-sigma RSS value. Using this 3-sigma RSS value of the deltas as a normalization factor, a weighting factor called an A-factor is obtained for each 3-sigma parameter variation. (Factor is always less than one.) Using these weighted parameters, a time (transient) response is run producing a peak value equal to the RSS value with time-consistent characteristics of other response parameters. This is a very effective approach if time-consistent loads are required. If time-consistent loads are not required, then the RSS values of peak responses can be used as the design load with reduced computer time. Monte Carlo analysis is another way of deriving a load with a given probability level. The number of cases required for convergence (if an unconservative estimate is required) is, in general, very costly. If a conservative estimate can be tolerated in the design, then a small sample Monte Carlo analysis can be run and the sample size correlation added.

A major problem occurs using either of these two approaches: the number of cases or trajectories required to achieve design load cases. The Space Shuttle used the A-factor RSS case in conjunction with a wind vector model for design. In this case, it was found that the wind vector model must be run every 15°, giving 24 different trajectories. Also, the wind-gust portion of the vector wind model could occur in any direction around the steady-state wind and could occur at any altitude. This means that for any critical design phase, usually Mach number, the above-cited set must be repeated. For Shuttle, Mach numbers from 0.6 to 3.0 were required to generate the various design loads for different portions of the vehicle. The wind model for one gust altitude is shown on Figures 8 and 9.

Taking a typical Mach number and wind model corresponding to that Mach number, the wind directions are run, generating design data. A problem occurs here in that the wind gust altitude must be iterated on to achieve the same Mach number for each wind direction. Once the run has been made for each wind direction and gust altitude, one must come back for that specific wind direction and gust altitude and run the parameter variations about the baseline case to determine the A-factor and the final one case time-consistent load case. All this is accomplished for rigid body only.

Figure 10 depicts the $q\alpha$ and $q\beta$ envelope determined for the different wind directions for one Mach number (1.05). Taking point A and running the other vehicle parameter variations (32 parameters for Shuttle) requires an additional 64 trajectory runs for these variations to determine the A-factor, giving the single point B. Repeating this for every 15° wind direction requires the product of 24 x 44 plus the 24 initial and 24 final runs for a total of 1,104 runs per Mach number. In addition, an elastic-body gust-response analysis must be run for each of these final 24 cases for each Mach number.

Doing a Monte Carlo analysis creates an equal number of cases. Both approaches are brute force and constitute a major problem in deriving design loads.

3. Describing Equations

How one forms the describing equations is an option. One approach uses generalized coordinates and generalized forces usually derived through Lagrange's equations. This approach is acceptable for most problems. The number of degrees-of-freedom (normal modes) required for simulation can be quite large. Also, if the environments, e.g.,

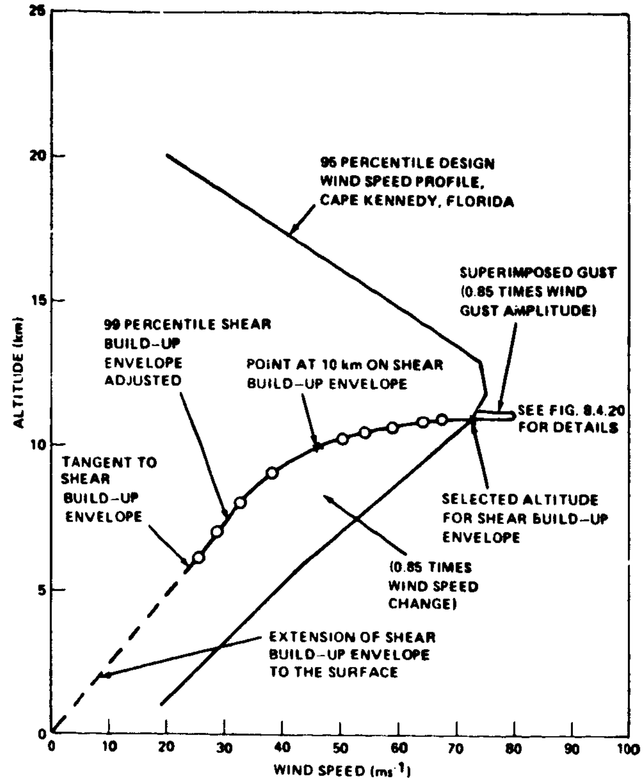


Figure 8. Example of synthetic wind profile construction, with relationship of wind shears and gusts assumed.

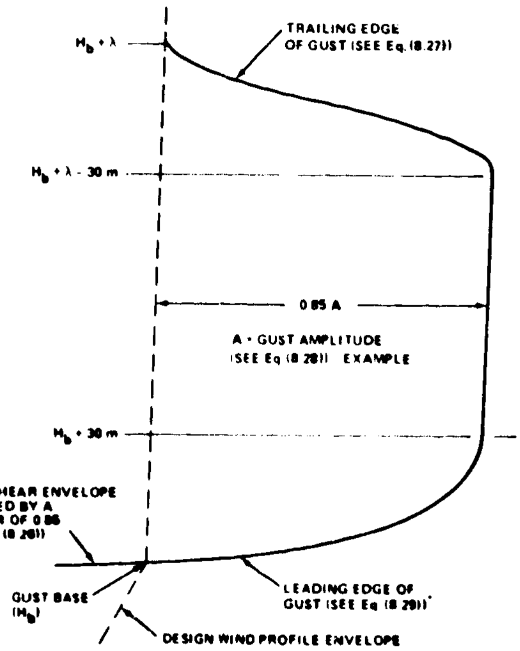


Figure 9. Relationship between revised gust shape, design wind profile envelope, and speed build-up (shear) envelope.

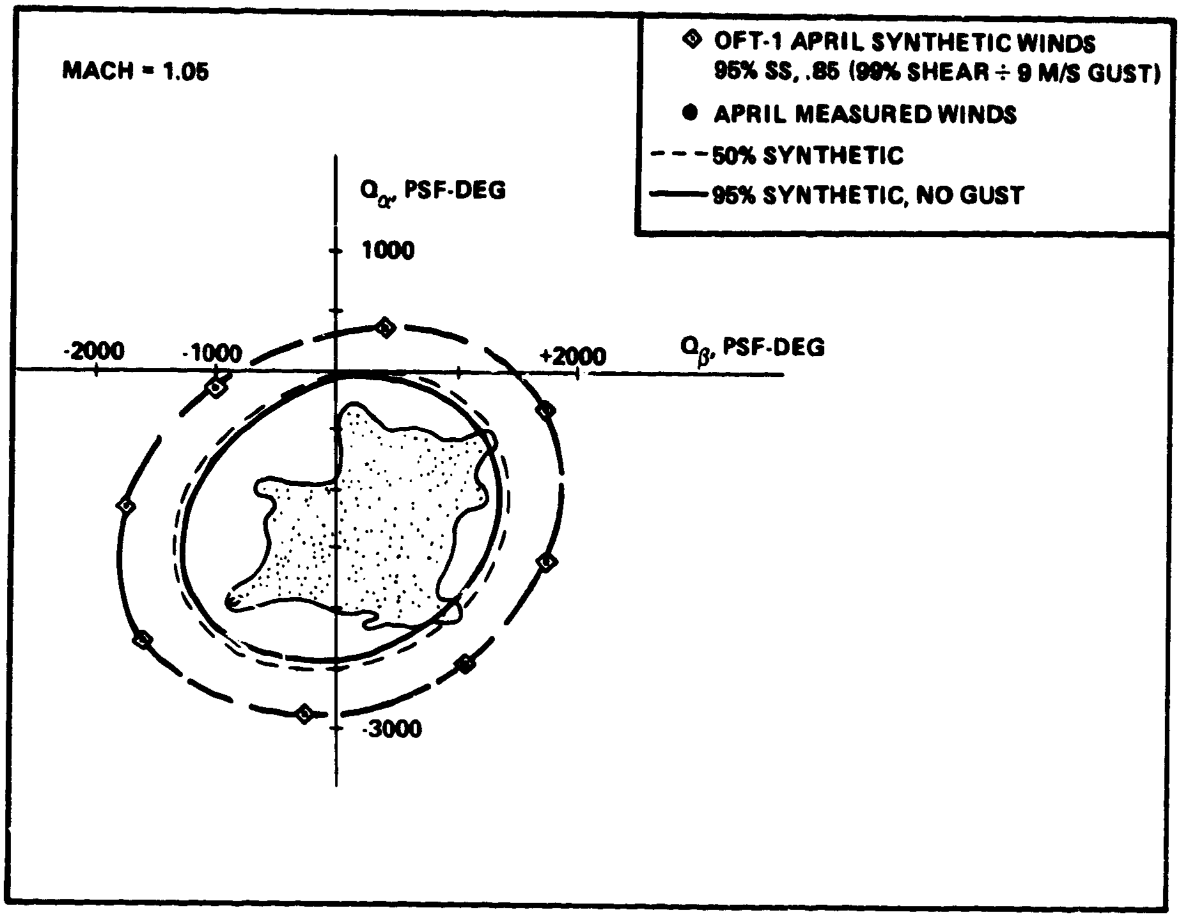


Figure 10. Qα/Qβ Envelope.

aerodynamics, are distributed over the structure, then this force distribution must be integrated across each mode shape in all directions to arrive at the generalized force. Equations formed in this way give only the modal generalized response as displacement, velocity, and accelerations. Additional transformations must be written for deriving running loads, forces, moments, etc., from these data. The loads transformation can be part of the response runs or can be generated in auxiliary programs using the response outputs as inputs.

When a system can be represented as a few simple rigid-body elements, spring-and damper coupled, then a lumped-mass approach where each mass response is described by coupled differential equations can be used and solved in the time domain. In this case, lumped forces are applied to each lumped mass.

4. Criteria for Selection of Analysis Approach

Several other techniques are available for describing the system, such as quasi-coordinates. It is not the purpose of this paper to explore each. The engineer can find the best approach for his application. General interrogatory criteria for choosing approaches include:

1. What number of modes and frequency content are required?

2. Are characteristics nonlinear or will linear analysis apply?

3. Must spinning parts be considered or does spin change modal characteristics?

4. Environment characteristics: Are aeroelastic effects required?

5. What coupling exists between control, structural dynamics, thermal, aerodynamics?

6. What design phase is the project in?

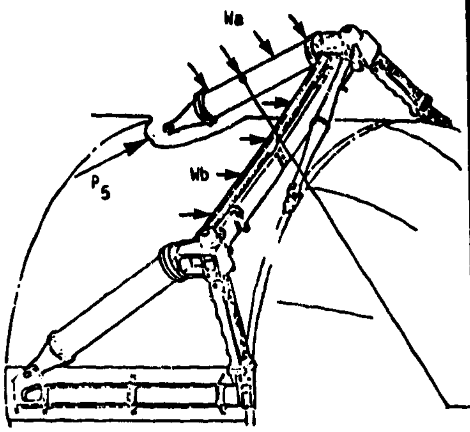
5. Interdisciplinary Considerations

Regardless of the approach taken, the external loads analysts must have established communication with the stress analysts to ensure compatibility of the external loads with the internal stress analysis approaches. Inherent in this is the compatibility of the force application node points with those of the stress model. Many times the stress model can be reduced and used as the dynamic model in the external loads analysis. In either case, both analysts must have a basic understanding of the other's models and approaches.

One approach that has been very effective is the use of load indicators, where load indicators are defined as an algorithm that relates external loads to internal stress and thus capability. In past programs, these indicators were formed after design verification for use in prelaunch monitoring for go or no-go decisions. What is needed is a form of these indicators starting immediately after preliminary design for all critical structure. These indicators obviously would be updated as the design progresses. Figure 11 is a typical load indicator for one portion of the Shuttle External Tank for use in prelaunch monitoring.

The advantage of building load indicators from the start is obvious. Loads and control personnel could rapidly conduct load alleviation trades and assessments without the basic structural impacts using load indicators until the final design verification phase, where the detailed stress assessment would be a requirement. This approach would not circumvent stress involvement; it would force stress analysts to work closely with loads analysts and require continuous reassessment of the fidelity of each indicator and the requirement for additional indicators. This approach could also shorten the overall analysis cycle time and give better insight to all involved.

It is important to remember at all times that regardless of the general approach chosen, there are required bending moments, shears, accelerations, etc., that must constitute a compatible set The exceptions to this judgment are single-point forces that go into struts, etc. They can be treated only from a force standpoint. Also, the generation of the moment and shear distributions increase commensurately with the length over which integration is carried out; therefore, it is better to integrate from both ends of the vehicle using the one most applicable to the station requiring load analysis. Payloads, in general, have no external aerodynamic pressure distributions and can be treated with forces and/or modal accelerations for generating internal loads. In this case, more liberty can be taken from a balance philosophy; however, consistency is always the best policy.



EQUATION 4.17

$$f_{max} = f_1 + \sqrt{f_2^2 + f_3^2} \leqslant 832$$

where:

$f_1 = -P_5 + 2.502 \times 10^{-5} P_5^2$

$f_2 = (6.448 - 1.762 \times 10^{-3} P_5 + 1.554 \times 10^{-6} P_5^2)\ Wa$

$f_3 = (2.436 - 7.646 \times 10^{-4} P_5 + 8.563 \times 10^{-7} P_5^2)\ Wb$

Wa = Total air load normal to thrust strut axis

Wb = Total air drag load on crossbeam, X-direction

$P_5 < 0$

EFFECTIVITY ( ) - DESIGN CONDITION	PL	LO	HQ	BA	PR	(PO)	OA	OE
		X	X					

CRITICAL AREA	RIGHT HAND THRUST STRUT (P_5) STRUT TUBE - MIDPOINT

	STABILITY	STRENGTH	OTHER
FAILURE MODE	X		

	INDICATOR	ANALYSIS	TEST DEMO'L.
FACTOR OF SAFETY	1.48	1.48	

INDICATOR ACCURACY + 4 %

Figure 11. ET load indicator.

In summary, three basic categories of analysis approaches must be dealt with: (1) dynamic models, (2) system models/simulation, (3) statistical evaluation. Following is a partial listing of current approaches for each.

1. Dynamic Models

   - Finite elements.
   - Lump mass.
   - Equivalent beams or plates.
   - Modal coupling.

2. Systems Models/Simulation

   a. Equation derivation.

      - Lagrangian
      - Quasi-static coordinates

b. Analysis approach.

- Nonlinear time-varying transient.
- Generalized harmonic analysis (PSD).
- Shock spectra.
- Coupled base motion.
- Impedance.
- Base motion.

3. Statistical Evaluation

- RSS'ing of peaks.
- A-factor.
- Monte Carlo.

F. Definition of Loads Combination Approaches

The discussion thus far has centered on body or airframe design loads. Just as important are the components, protuberances, and subcomponent loads. In many of these cases, the design loads are a combination of the frequency system driven loads or accelerations, local pressure distributions, and high-frequency acoustics excitation. Two problems or questions are apparent, (1) How does one calculate these loads? (2) How are the loads from the different sources combined?

Component loads calculations are usually done using base drive, Miles formula, or some type of shock spectra analysis. The low-frequency loads can usually be extracted directly from the system analysis by weighting node point (c.g.) accelerations. Pressure distribution effects are straight static loads determined by proper integration over the component or protuberance area.

Loads combination depends on the amount of conservatism one can put in without causing undue design impacts and weight penalties, both from ultimate design loads and fatigue standpoints. Since many of these components are fatigue sensitive and must go through development, qualification, and acceptance testing, the determination of these approaches is critical. One way is to sum up the peaks in each axis producing a conservative load. Another is to attempt to make the loads time consistent. Certainly, the loads should be pseudo-time-consistent from the event standpoint. In other words, do not combine liftoff peaks due to systems with max q acoustics, etc. If different safety factors are applied for high-frequency loads than for low-frequency loads, then these must be included before determining the combined external load. This means again that communication between loads and stress must be well established. Loads combination is a key area; many factors must be considered. This is a specialized area in itself that is beyond the scope of this paper, but, in which the load engineers must be very knowledgeable.

G. Preliminary Definition of Flight Operations Approach

The flight operations approach in the past has been part of the margins; or, said another way, allows for lower-risk higher-launch probability. For example, the Apollo launch vehicle was designed for the 95% worst-month wind speed in conjunction with an RSS 3-sigma wind gust and shear as the nominal wind. All parameter variations were about this mean. For launch operations, the vehicle was flown biased to the monthly mean wind speed adding significantly to the load margins available for launch commit. In addition, loads were calculated for prelaunch measured winds starting 16 hours prior to launch and continuing up to 1½ hours prior to launch. Launch safety was thus ensured through a special-shaped trajectory and a launch commit/constraint criterion. Present systems probably cannot use the conservative approach used for Apollo. For example, Shuttle used the monthly mean wind biased trajectory in the design loads phase. In operations, Shuttle plans to use day-of-launch trajectory update (I-loads) based on winds measured that day. Early launches will use a loads launch constraint procedure also.

It is very important that preliminary approaches be established early so that the loads engineer and environmental engineer can factor these considerations into the design loads. The more accurate the environment and loads models are, the more nonconservative one can go, for example, in wind biasing. Also, if launch time is not critical, the less conservative loads can be used in conjunction with launch constraints. It should be clear also that the loads engineer should be key in determining this operations approach so that undue risks are not taken.

H. Preliminary Definition of Approach for Flight Verification of Environments and Resulting Loads

A very important aspect of all loads work is the flight verification of both the environments and resulting loads. With the development of repeated use of the same configuration or multi-use (reuse) of a single vehicle, extending its performance and reducing margins are paramount. The loads engineer is constantly asked, for example, can structural weight be taken out? Can a heavier payload or different mission be launched? The basis for these decisions is a flight verification of both models and environments. Thus, the extensive use of both Atlas Titan and Delta launch vehicles has allowed the establishment of detailed environments and responses for various classes of payloads (References 38-47). This data base allowed for more efficient payloads and higher payload capabilities for these vehicles.

In addition, it is the accepted practice to upgrade launch vehicle performance through engine and propulsion system upgrading and weight reductions. The experimental verification of the non-upgraded system serves as the anchor for this upgrading.

The loads engineer must, therefore, plan for special instrumentation during development flights, and for sustaining instrumentation on all flights to achieve these desired results. The adequacy of the plans must be established early, for this determination is a fundamental part of loads engineering. Clearly, the instrumentation, data acquisition, and data evaluation system must be geared to the frequency and expected response levels of the configuration. Since these systems are now within current technology, the engineer's main concern should be instrument definition and location. The sensitivity analysis as well as all loads cycle serve as the basis for this selection.

The load-indicators approach discussed earlier is a very viable option for this verification phase and solves in the optimum way the problems outlined before.

In summary, the verification approach selected is key to the loads analysis approaches used during the whole design cycle.

I. Payload Loads Consideration

The discussion thus far has dealt with loads in general. Payloads follow these general guidelines; however, many special considerations must be added if payloads are to be handled efficiently and accurately. A fully operational Space Shuttle will offer science the opportunity to explore near-earth orbit and finally interplanetary space on a nearly limitless basis. This multiplicity of payload/experiment combinations and frequency of launches place many burdens on dynamicists to predict launch and landing environments accurately and efficiently. However, the challenges do not stop there. Operational environments are usually mild from the loads standpoint; thus this part of the design criteria is stiffness, and not strength, driven. The launch portion also has stringent stiffness requirements that may not be compatible with the operational ones. Herein lies the dilemma. The payload/experiment must survive the launch and landing environments, yet meet stringent requirements while in orbit. Two major problems are apparent in the attempt to design for the diverse environments: (1) Balancing the design criteria (loads, etc.) between launch and orbit operations, and (2) developing analytical techniques that are reliable, accurate, efficient, and low cost to meet the challenge of multiple launches and payloads. The large variety of payloads and their special requirements mean that the analyst must have a whole cadre of approaches and analysis tools. Although present analytical approaches are accurate, they are based on detailed modeling approaches, which require laborious efforts of compiling, sorting, and evaluating many pieces of data. This does not allow time for the required number of iteration cycles, and sometimes results in improper trade assessments. Complex analysis approaches lead to input-type errors that are hard to find, further compounding the situation.

A large portion of the transportation system (Shuttle) design criteria is driven by max q environment, while payload loads result from short-term transient loads (inertial) at liftoff and landing. For max q environments, operational techniques such as wind biasing and wind constraints are available to reduce loads. This usually allows compensation for late changes in the environments without design changes. Due to the characteristics of payload loads (driven by liftoff and landing), this option is not open.

Furthermore, the problem is compounded by the fact that the Shuttle transportation system and the payload configurations are very complex, unsymmetrical, dynamic systems with high modal density. The opportunity for dynamic tuning is an ever present reality. Low-damped systems that tune two to three subsystems are very sensitive to small parameter changes and require many combinations of parameter variations to develop design loads, and thus entail numerous computer runs which are both costly and time consuming.

Obviously, the loads engineer faces many challenges that sometimes seem insurmountable. However, in the case under discussion, this is not true. There exists a very strong analytical base and much experience for structural modeling and loads analysis. Also, the different classes of problems requiring solution are well defined. With the right focus and effort, the goals are reachable. It should be pointed out that to attack these problems, the approach chosen for analysis is unique for each type or class of payload and cannot be generalized further. Thus, to simplify the choices, three classes of payloads have been chosen (Table 1). The first class is composed of special-purpose, long-operation-time payloads that require very accurate design criteria, hence are weighted towards the use of detailed time-consuming analysis approaches. The second class is generally composed of reusable carriers with short operation time and many complements of experiments and is therefore weighted toward simplified, quick analysis cycle time, utilizing conservative approaches. The third class, propulsion stages with attached payloads, is weighted toward very accurate, unconservative approaches with many trades in terms of isolation. These payloads are weight limited due to performance requirements (Reference 48).

TABLE 1. CLASSES OF PAYLOADS.

CLASS I: UNIQUE, SPECIAL PURPOSE PAYLOADS (SPACE TELESCOPE, HEAO)

- LARGE, EXPENSIVE, SENSITIVE UNITS
- LONG OPERATIONAL LIFETIME
- STRINGENT OPERATIONAL REQUIREMENTS
- ACCURATE ENVIRONMENTS NECESSARY

CLASS II: STANDARD CARRIERS (REUSABLE) WITH VARIOUS COMBINATIONS OF EXPERIMENT COMPLEMENTS (SPACELAB, LDEF)

- SHORT TERM OPERATIONS
- SMALL TO MEDIUM SIZE EXPERIMENTS
- CONSERVATIVE ENVIRONMENT CRITERIA ACCEPTABLE
- IN GENERAL, NOT WEIGHT CRITICAL. CAN OFF LOAD EXPERIMENT COMPLEMENT

CLASS III: WEIGHT LIMITED (PERFORMANCE), REUSABLE STAGE PLUS PAYLOAD (IUS, SEPS, VIKING)

- TRANSPORTATION SYSTEM ENVIRONMENT CRITICAL
- PAYLOAD DYNAMIC CHARACTERISTICS CRITICAL
- STAGE/PAYLOAD DYNAMICS CAN INTERACT AND VIOLATE STS INTERFACE REQUIREMENTS

One method for reducing complexity and analysis time open to the loads engineer is the judicious use of frequency constraints on subassemblies and experiments placed on the payload carrier. Using this approach, however, a balance between low-and high-frequency environments must be obtained (Figure 12). Also, in this case, the frequency content of environment must be predictable. The problems in using this approach are indicated on the figure. Mainly, the engineer must ensure that the frequencies he chooses do not amplify high-frequency acoustic induced loads and create bigger ultimate design load requirements. This is particularly true for payload components and experiments where the high-frequency acoustic loads are the design driver. If these conditions can be met, then simplified models and analysis approaches can be used at much reduced cost and time.

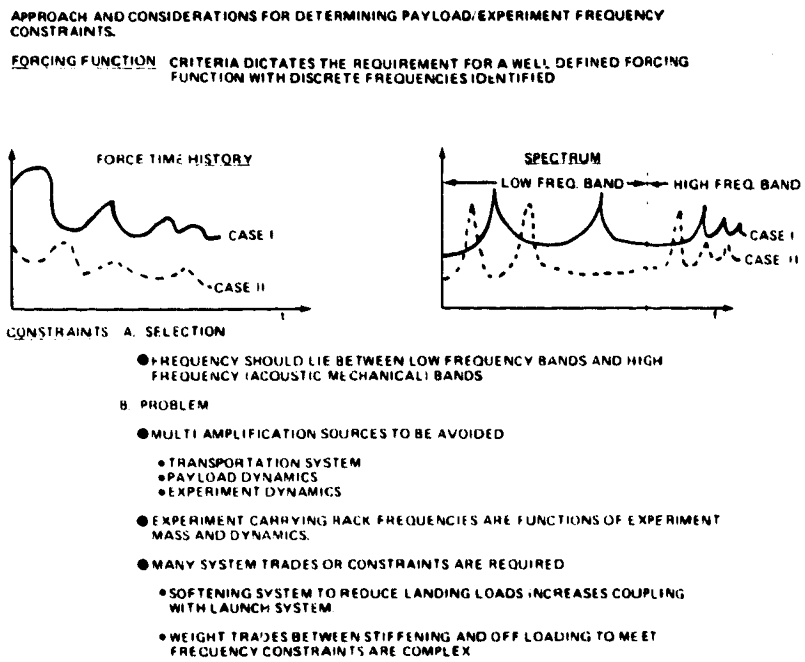


Figure 12. Payload/experiment constraint problem.

Methods the engineer uses in loads analysis fall into two broad categories: (1) methods for deriving structural models of payload and payload coupling to systems structural dynamic models and (2), methods for determining payload responses, thus loads. A discussion of modeling and subassembly model coupling techniques was given earlier.

This individual and systems modeling is depicted on Figure 13 as well as how the resulting systems model is used.

In the earlier section only a limited discussion occurred for the response analysis approaches for payloads. MSFC has used all of the current technology approaches in analyzing payload loads. Since payloads are designed by two events (liftoff and landing) for Shuttle and these responses are nearly all dynamic in nature, MSFC's basic approach has been an all-up systems approach. The following paragraphs discuss the different approaches.

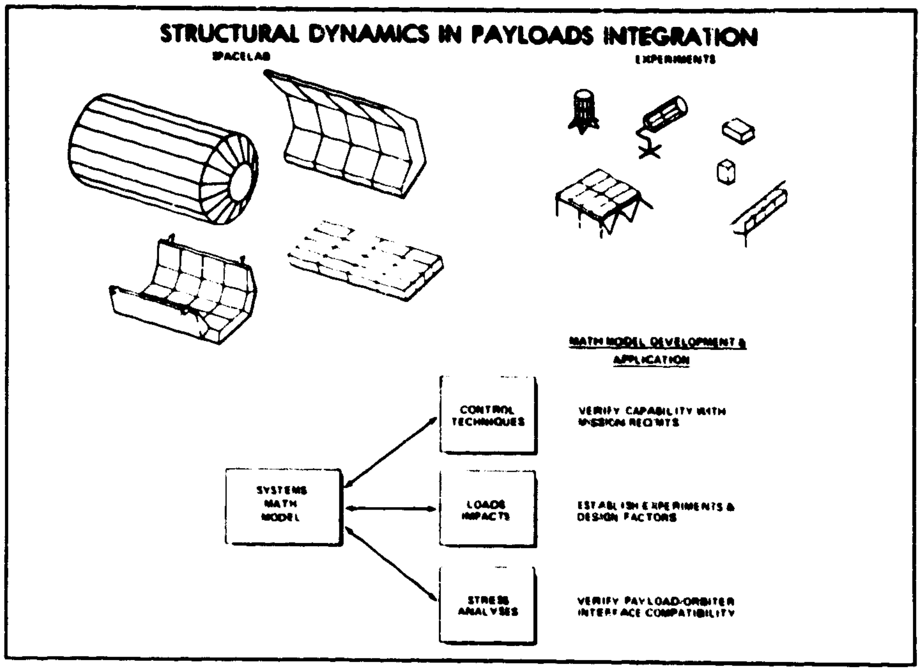


Figure 13. Payload integration math model development.

1. All-Up Systems Approach

The approach can be handled in two ways. The first approach takes all the forces and vehicle parameters and does a 3-sigma design load using either the 2-sigma worst-on-worst approximation or the A-factor transient time response analysis discussed earlier. In the other case, the transient time response analysis can be run by applying a set of launch-vehicle-provided forcing functions to the complete all-up vehicle. These forcing functions have been derived for liftoff and landing under the assumption that the dynamics of the payload (absent in forcing function derivation) will not alter the external forcing functions. These forcing functions for Space Shuttle were developed using a 2-sigma worst-on-worst approach providing, in general, 10 sets of forcing functions for liftoff and 4 forcing function for landing. The shortcoming of this approach is that the parameter variations have not been chosen to maximize the load for a particular payload. It does, however, save much computer time since one common set of forcing functions can be supplied to each payload customer along with a dynamic modal model of the Shuttle without a payload. The user then can use a dynamic model of his payload, couple it with the Shuttle modal model, apply the provided forcing functions, and thus arrive at a set of design loads. Figure 14 depicts this approach.

In payload responses discussed in Section II, this has been the prime approach used; however, the cost and turnaround time associated with all-up analysis has pushed the development of some payload-alone system loads approach.

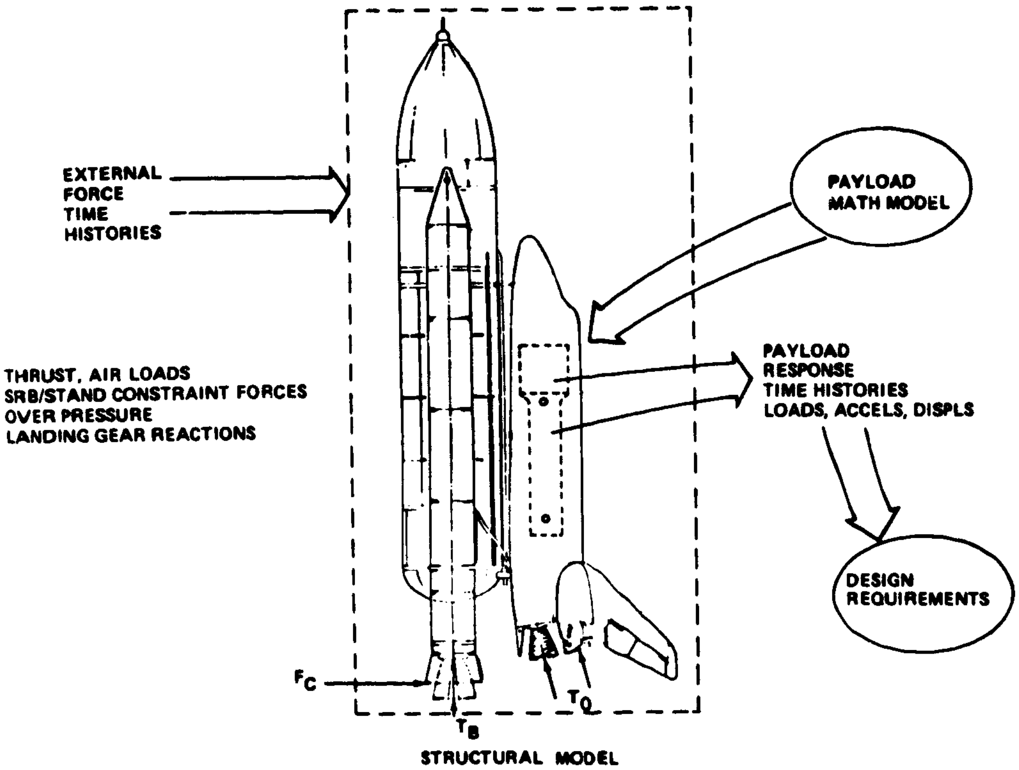


Figure 14. Payload loads approaches.

2. Payload System Approach

Several systems techniques exist (Reference 44) for analyzing only the payload system. The oldest of these that has found extensive use is the base motion drive. This approach uses the payload-to-carrier interface accelerations derived from flight data or analysis as the input force to a payload dynamic model. The resulting loads in this case are always conservative, since the response of backup attach structure is not present. MSFC has developed a new approach that accounts for this feedback; however, it is unproved and subject to convergence errors. Figure 15 shows the two methods and compares them.

There is another class of methods that falls into the category of shock spectra and impedance methods. These approaches attempt to get an envelope load without running all the numerous cases run in the past. Also, these approaches do not require a modal analysis of the payload/carrier systems. Figure 16 summarizes these approaches.

A detailed discussion of all available techniques showing comparison data has been published by JPL (Reference 44). This reference is recommended if one is interested in the history and present state-of-the-art techniques for payload loads.

The techniques used by MSFC depend on the payload classification and design phase discussed earlier. Also, extensive use has been made of frequency constraints on components and of analysis uncertainty factors in early design phases. A discussion of the rationale for the uncertainty factor follows.

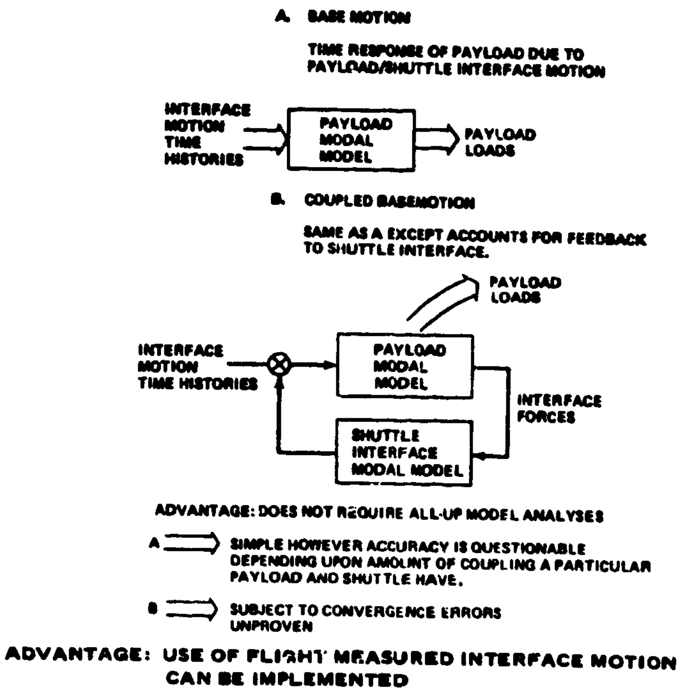


Figure 15. Payload system approaches.

ADVANTAGES:

SIMPLICITY – DOES NOT REQUIRE MODAL ANALYSIS OF ALL UP SYSTEM

DISADVANTAGES

- SENSITIVE TO DAMPING ESTIMATES
- LEADS TO HEAVY STRUCTURAL WEIGHT
- MAY NOT ALWAYS BE CONSERVATIVE

Figure 16. Shock spectra and impedance method.

Uncertainty Factors for Equivalent Statistical Quantification - Normally, the loads engineer needs to define a 3-sigma type load. As discussed previously, the launch vehicle accomplishes this by varying vehicle parameters and then using the A-factor approach. The payload not only is sensitive to the vehicle system parameters but also has the uncertainty of the payload dynamic characteristics. Attempting to vary the dynamic characteristics in conjunction with the carrier system parameters is basically an impossible task. This has led to looking at some equivalent means of accomplishing the accounting for these unknowns. To accomplish this task, it is necessary to establish some rationale to the approach that is patterned after the standard A-factor approach. The following chart (Figure 17) shows this approach. In this case, the payload load is split into three parts: the nominal load, the delta load due to carrier system parameter variations, and the delta payload load due to payload tolerance variations.

- STATISTICAL APPROACH FOR DESIGN LOAD DEFINITION
  - DESIGN LOAD = 3 SIGMA LEVEL
  - RECIPE TO ESTABLISH 3 SIGMA LEVEL LOAD
    (1) ESTABLISH NOMINAL LOAD LEVEL USING NOMINAL VALUES FOR SYSTEM VARIABLES
    (2) ESTABLISH LOAD INCREMENTS ABOVE NOMINAL DUE TO 3 SIGMA TOLERANCES ON SYSTEM VARIABLES
    (3) ESTABLISH LOAD TOLERANCE BY RSSING OR SOME EQUIVALENT PROCEDURE
    (4) DETERMINE A-FACTOR FOR TIME RESPONSE SOLUTION OR EQUIVALENTLY

$$L = L_{NOM} + L_{RSS}$$

  - FOR A LOAD, L, IN A SHUTTLE PAYLOAD

$$L = L_{NOM} + \left[\sum_i (\Delta L_{Si})^2 + \sum_i (\Delta L_{Pi})^2 \right]^{1/2}$$

ΔL_{Si} = LOAD INCREMENTS DUE TO PERTURBATION OF SHUTTLE SYSTEM VARIABLES

SHUTTLE SYSTEM VARIABLES	LIFTOFF = THRUST, WIND, OVERPRESSURE, SHUTTLE MODEL, ETC LANDING = SINK SPEED, WIND, ORBITEM MODEL, ETC

ΔL_P = LOAD INCREMENT DUE TO VARIABILITY IN PAYLOAD MODEL

Figure 17. Space telescope loads criteria.

Taking this equation for some given payload location and dealing with the RSS load deltas due to payload parameters leads to:

(1) $L = L_{NOM} + [(\Delta L_S)^2 + (\Delta L_P)^2]^{1/2}$

where

L = 3-sigma peak load at some payload station

L_{NOM} = Nominal value of peak load

ΔL_S = 3-sigma increment due to Shuttle System

ΔL_P = 3-sigma increment due to payload variability

Equation (1) can be rewritten in terms of an uncertainty factor that is equivalent to payload model variations.

$$(2)\quad L = \text{U.F.} \left\{ L_{NOM} + [(\Delta L_S)^2 \text{ to}]^{1/2} \right\} = \text{U.F.}\,(L_{NOM} + \Delta L_S)$$

Rewriting, using equations (1) and (2) gives:

$$(3)\quad \frac{L}{L_{NOM}} = 1 + \left[\left(\frac{\Delta L_S}{L_{NOM}}\right)^2 + \left(\frac{\Delta L_P}{L_{NOM}}\right)^2\right]^{1/2} = \text{U.F.}\,\left(1 + \frac{\Delta L_S}{L_{NOM}}\right)$$

Solving equation (3) for an equivalent uncertainty factor leads to the results shown on Figure 18. Plotted is uncertainty-factor-induced nominal loads. Vertical lines indicated the lowest value, mean, largest value, and 3-sigma high values for $\Delta L_S/L_{NOM}$ observed for payload net load factor responses for the Space Shuttle. It is clear that if the launch-vehicle-induced delta payload load ratio is around the mean value observed, then an uncertainty factor of 1.15 would cover a payload uncertainty ratio of 1.5. Using this table and some basic information of any carrier payload system allows the engineer to account for payload variations without running additional cases. It is noted that tuning effects between the payload modes and the Shuttle system have not been accounted for in this development. Significantly larger uncertainty factors are required for payload components which may become resonant within the range of expected system parameter variations.

Frequency constraints are specified on payload subsystems to minimize the dynamic magnification associated with tuning. For example, the system response frequency during landing is around 16 Hz. It is desirable to get the component or payload experiment out of range of tuning such that there is no dynamic amplification. A minimum frequency of 25 Hz on subsystem frequencies was chosen for this limit and applied for Spacelab experiments. If a support structure (such as a platform) is mounted to the primary structure, then it has the 25 Hz constraint; therefore, any experiment mounted on this secondary support would then have a 5 Hz lower frequency constraint. Use of this approach has allowed loads calculation with dynamic models of experiments (mass simulated).

Utilizing uncertainty factors in conjunction with frequency constraints cuts analysis time significantly. Obviously, the uncertainty factor must be an evolving number becoming smaller for each design cycle.

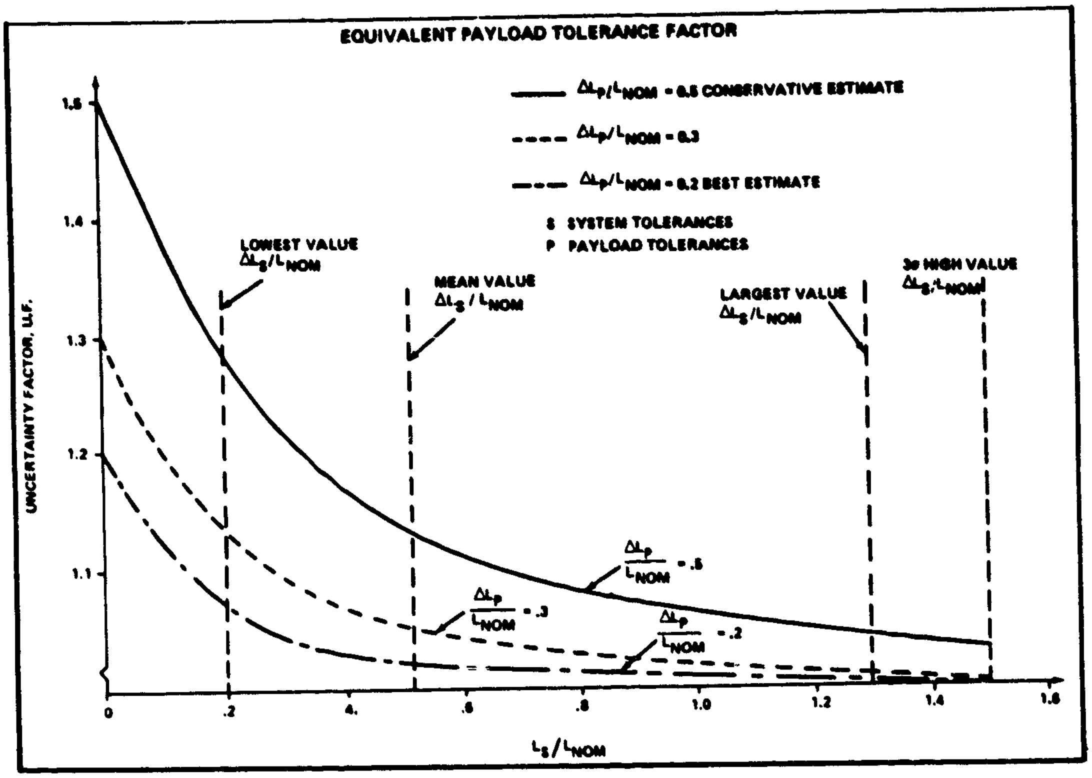


Figure 18. Equivalent payload tolerance factor.

In summary, one of the biggest challenges loads engineers face today is how to reduce significantly the analysis time without being ultra conservative and yet keep risks and costs at an acceptable level. The prior discussion indicates some potentials, but can only serve as a starting place.

SECTION II. FUTURE PROGRAMS

A. Transportation Systems

Several different approaches to future transportation systems have been looked at in the conceptual stages. Others are beyond the conceptual stages. The first category is already upon us and deals with performance enhancement of the present Shuttle configuration. The enhancement techniques first of all attack weight savings that take advantage of better environment definitions and structural capabilities definitions. This brings the loads analysts into the middle of the problem. The more accurately he can define the loads the more weight can be removed. This effort is already in progress for the Space Shuttle. A detailed design to lighten the External Tank has already been accomplished. Here, both the thermal and external loads environments have been massaged to reduce weight. In addition, more optimized design and materials choices have also been used. Further savings can be made after Shuttle flies and the environments are further defined. The tank has the greatest potential for accomplishing this type of weight savings. since its weight and payload weight are particularly pound-for-pound and the tank is not reusable. This means that at a given time, the manufacturing line can be interrupted and the lightweight design started.

The Solid Rocket Booster is to be reused twenty times and thus offers some potential for weight reduction; however, its payload-to-weight ratio is less than 10 to 1. Being pursued for SRB is the use of a fiber filament case and higher burn rates. Obviously, reducing the Orbiter weight is directly related to payload. Studies in thermal protection systems, etc., are being pursued for Orbiter upgrading.

The next category of Shuttle performance is through the use of propulsion enhancement: (1) upgrading the Shuttle Main Engines to 115% or 130% of rated power level, (2) increasing the SRB performance through grain shaping, etc., (3) adding auxiliary propulsion devices such as strap-on solids or liquid boost modules. These problems are being pursued using the same approaches for loads as have been used in the past. The tools should be adequate for these enhancements and, therefore, greater payload to orbit. Again, as has been stressed throughout this report, the system aspects must be fully analyzed as well as all the interactive disciplines. The additional load paths, more dynamic elements coupled into the multi-body Shuttle element, more acoustical energy, more protuberances, etc., all offer complicating factors, all of which must be understood. Effort is underway to define criteria for these studies and design efforts. Initial parameter sensitivity studies are underway. Initial results are promising that major advance (40 to 60%) can be made in Shuttle performance (payload to orbit).

The third approach would develop a completely new booster, say flyback, but keep the present Orbiter and tank or some other such combination. The new booster could then evolve to greater payloads with a new Orbiter (Reference 49).

The final approach would be a total new system. Starting a new system would allow the use of more optimum design approaches, such as control configured vehicles, integral mold lines, newer materials, automated design processes, high-performance propulsion systems, etc. Here, the present techniques need further development if the potential is achieved. Section IV will deal with these areas.

Upper stages or interplanetary stages are under design. Here, the major loads environment is introduced from the launch transportation system. This will require nothing new, basically falling into the category of payload loads analysis discussed earlier.

B. Large Space Structures

Large space structures loom as the next system or systems viable on the horizon (References 49, 50, 51, 52, 53, 54). Present concepts and preliminary designs of these systems point towards a stiffness instead of strength driven design. This means that, in general, the loads engineer will be dealing with responses instead of loads, or conceivably will be working closely with the control people to ensure correct dynamic simulation.

The one exception to this is the area of docking and handling loads. Docking loads require very detailed, nonlinear structural dynamic and control models and simulations for loads calculation. Very good models and simulations were generated for the Apollo Program. These should serve as a good starting point for these studies.

Large space structures, or more precisely, the different programs or uses of large space structures in space, levy a unique set of requirements on design and, therefore, on technology. Not only must some configurations have specific orientations in space, but in addition their shape must be controlled. The structure must be assembled or manufactured in space or both. This leads to growth accommodation requirements, joints, and various roles of man/manipulator interactions. Size limits ground test as do design requirements that are stiffness, instead of strength driven. Digital control systems need the fullest exploitation to lessen the structural design impacts and reduce the need for development of specific materials.

Large space structures technology must develop simulations that are large scale, nonlinear, and time-scaled with growth potential. This is not only important for design, but for realtime support during buildup and operations. Skylab demonstrated this through the use of a time-scaled Skylab orbit simulation that includes dynamics and control to plan practically daily the most optimum maneuvers for experiments in terms of fuel usage (RCS propellant). In addition, simulations are needed for optimal design approaches, man/loop interaction with system and closed-loop control, and special trade studies. To accomplish the development of good simulation requires, in addition to other things previously discussed, the development of vehicle performance criteria and means of simplifying the simulation while retaining all essential characteristics.

In the area of analysis, techniques for analysis using all the uniqueness of digital control systems are needed, e.g., multi-sample rate, variable skip, and nonlinear filtering. The old problem of state estimation is with us and has even more importance in large space structures without detailed all-up dynamic test verification. Testing is a real problem. The low-g environment coupled with the structure size basically eliminates ground testing. Some means must be devised to couple together limited ground testing (component and scaled) with on-orbit testing and analysis in an optimum way as a verification tool.

Figure 19 lists some of the key issues in various disciplines important to system dynamics and the associated trade studies of these large space systems. The listing is not intended to be all inclusive and is biased by the author's experience. Major issues occur in each discipline area as well as between the disciplines; e.g., in the integrated dynamics area, key issues involving test and analysis roles and the resulting technologies as discussed previously. How to model and simulate nonlinearities is a key area, as well as whether to design for stiffness requirements structurally or depend on control systems to provide the equivalent stiffness. The source for control authority is very important as is the sensor choice, location, and control logic. In the area of design criteria, the choice of unconservative approaches for parameter variations and methods of combining these in design studies is necessary if low cost/high reliability are to be achieved. Other key issues deal with choice of materials; role of man in the loop; verification approaches for models; and the role of on-orbit test, control system update, etc., versus all-encompassing ground-test and development. The approach of desensitizing the system to variations of system parameters versus brute force design approaches could lead to efficiency and cost savings.

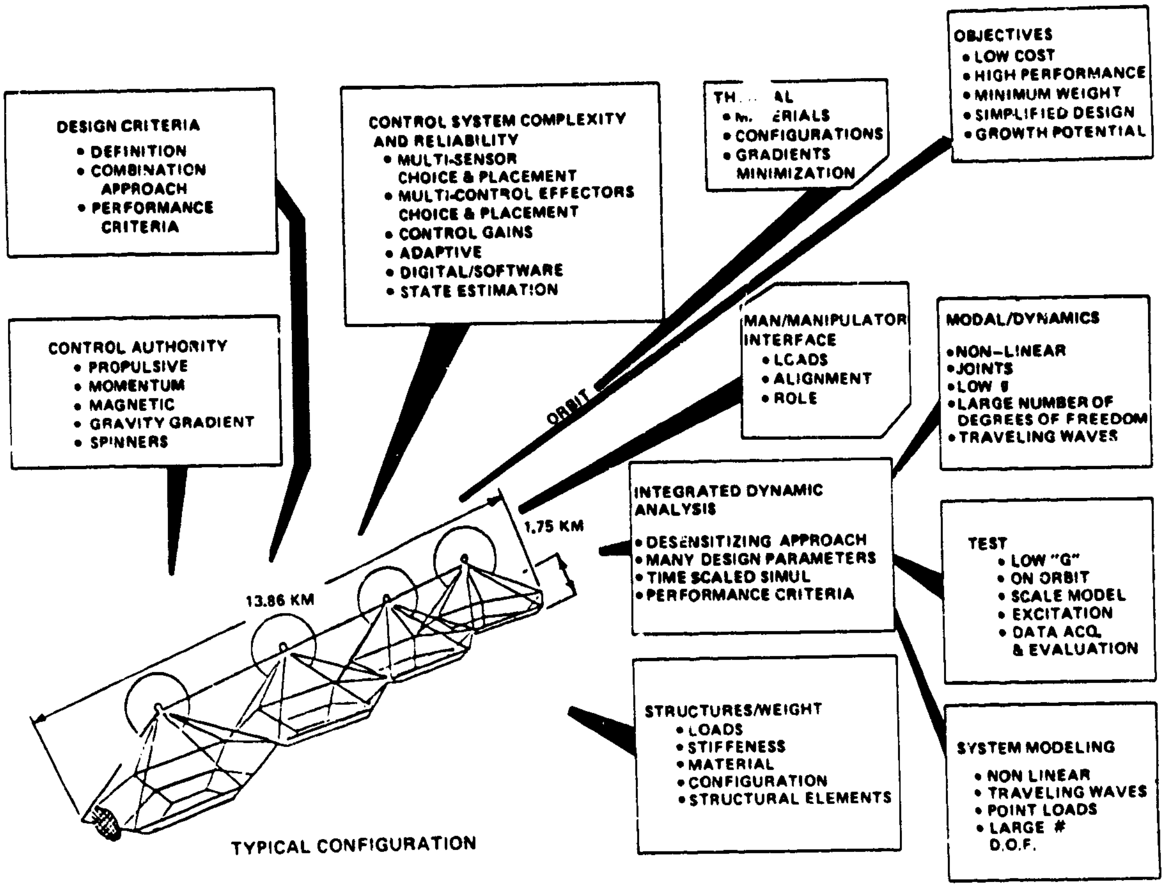


Figure 19. Key issues in various disciplines.

The previous chart developed the key issues in LSS technology. Figure 20 addresses a partial listing of the trade studies that arise from the key issues. They are trades between control system complexity and modal data accuracy verification requirements, structural beefup versus using the control system to augment structural damping and stiffness, on-orbit testing and control system update versus ground testing, and distributive control concepts versus structural design requirements. Additional trades between control, structural geometry (load paths), materials, and thermal are also indicated. With the cost and weight constraints that drive large space programs, advantage must be taken of all possible savings. It is clear that identification of the real advantages of any given approach cannot be quantified until some basic system configuration analysis has been conducted. As stated earlier, this approach must be taken in order to drive out the key issues and trades.

In summary, the approach for large space structures must be the systems approach discussed earlier. The technology implications are (1) on-orbit dynamic testing, (2) geometric and material nonlinear analysis, (3) structural control optimization approaches, (4) modal truncation approaches, (5) modal section approaches, (6) time reduction of analysis, (7) modal accuracy requirements, and (8) joint characterization.

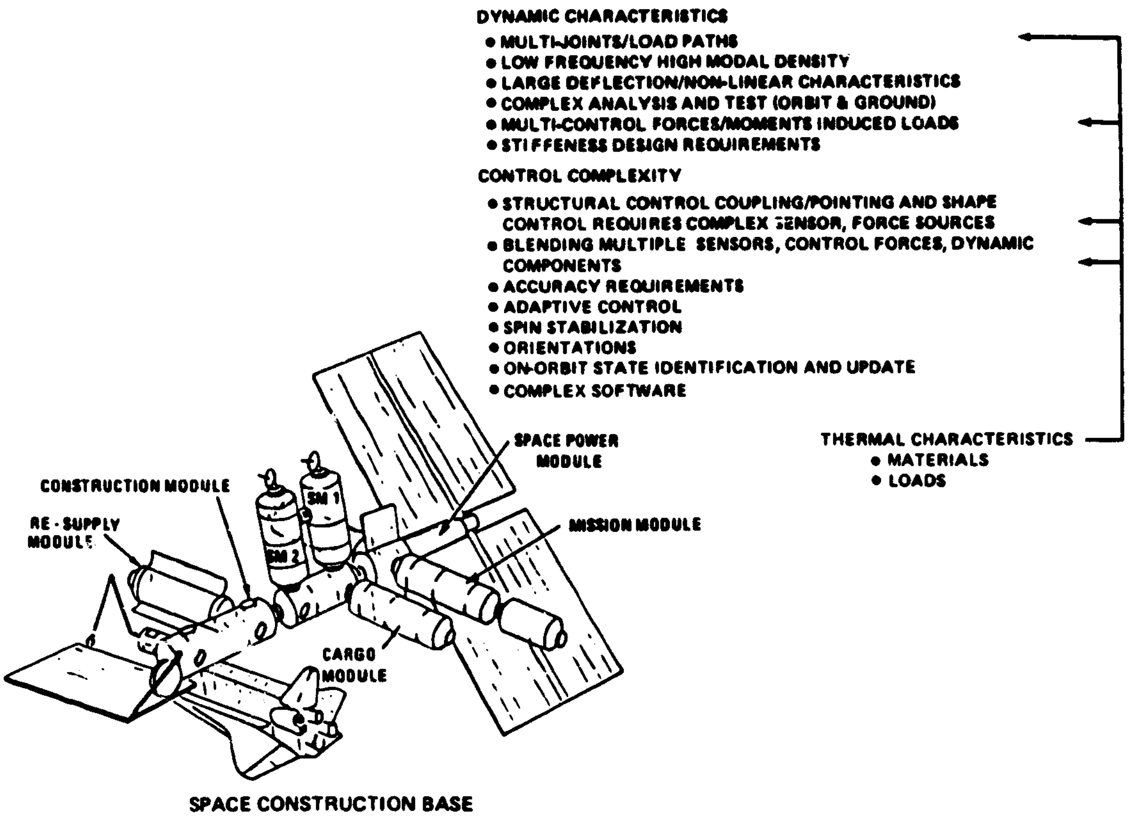


Figure 20. Partial listing of key trade studies.

SECTION III. SUMMARY/TECHNOLOGY IMPLICATIONS

In summary, loads work conducted at MSFC and loads work observed at other NASA Centers and at NASA contractors bear out the need for a systems approach coupled with detailed sensitivity analysis.

Present approaches to loads analysis and the resulting loads cycle are very long in time and laborious, creating many potentials for errors as well as high cost and less than optimum designs. In most cases, final loads analyses are completed after the vehicle flies.

Load engineers must have a broad knowledge of other disciplines. They must be able to communicate requirements and definitions clearly to these disciplines to get good environments, analysis support, etc. The problem of ensuring the proper integration and communications of all involved disciplines is probably the most important and challenging job loads engineers face. In fact, it seems that for now and the future, loads engineers should be cross-discipline trained with specialization occurring only after several years of broad experience. The process could be reversed, detailed specialization first, then cross training.

As stated clearly by Amos and Geotz (Reference 50), the need to meet specific performance requirements will drive each activity of the design process to accurately address its effect on the final product. This will shift the emphasis from the validation phase to the design phase. Obviously, this means better system analysis, more indepth discipline analysis, improved statistical techniques, and much more efficient data management techniques. In addition, this shift will drive the system to depend very heavily on analysis, while in the past, test was the prime mode.

Clearly, the need exists for much improved techniques for data processing, pattern recognition, etc., so that the engineer can drastically reduce the amount of data to look at and evaluate. Certainly, microprocessors, special filters, etc., should be brought into the loads world. The volume of data requiring evaluation is prohibitive leading to errors, etc. This is a prime area for research.

Beyond these, communication and training reemphasis are requirements in basic loads technology. The experience in Shuttle and its payload design efforts has led to several clear cut questions or technology issues that require resolution. The following list summarizes the issues in question form.

Basic Loads Questions or Issues

1. How does one treat probability analysis and construct a probability statement for a nonlinear or nonstationary system, such as Shuttle liftoff loads?

2. How does one handle aerodynamic tolerances in design where aerodynamic distributions are required in loads generation?

3. How does one model input environments to account for forcing function and dynamic tuning in a realistic way without undue loads penalties?

4. What is the best way of combining high-frequency (acoustic) induced loads with the low-frequency loads for design criteria?

5. To what extent should the planned flight operations approach influence design loads approaches?

6. Techniques or means of simplifying dynamic models to reduce analysis time and complexity.

7. Modal truncation and selection criteria for reducing analysis time and complexity.

8. How does one adequately determine vehicle parameter sensitivity for systems that have complex load paths and a high degree of element dynamic tuning?

9. What is the most efficient way of combining parameter variations to achieve a set of design loads?

10. How can one realistically reduce the number of load cycles required during design and verification?

11. How can one account for design changes (mass and stiffness) without conducting all-up load cycles?

12. What is the proper use of frequency constraints to simplify loads analysis?

13. How does one handle the dynamic tuning potential of payloads with the transportation system?

14. What is the most appropriate way of defining a transportation system forcing function for payloads without redoing to maximize loads for each payload?

15. How does one ensure that there are consistent models and contraints of all contractors and elements required to build total model and do loads analysis?

16. How does one define and verify analysis and data management techniques that will drastically reduce load cycle time.

17. In high performance systems, such as the Shuttle SSME which performs under adverse thermal and fluctuating pressure environments, how does one design for fatigue for which the material characteristics (SN curve) are very flat; hence the lifetime is very susceptible to oscillating stresses and the system is very weight sensitive?

18. Defining environments and calculating loads for protuberance are a major design question. How does one ensure that all these protuberances get proper attention and an adequate design?

19. What are the most promising techniques for reducing computer time for modal and loads analysis?

20. How can one extract aerodynamic data from flight data as a means of verifying operational data base?

21. How much of potential operations margins should one use in design of high performance vehicles?

22. What is the approach for treating failures in conjunction with parameter variations?

23. In high-performance systems, how much should one rely on time-consistent loads versus max/min?

24. Is it appropriate to use uncertainty factors? When and how?

25. How does one ensure that empirically determined environment data are compatible with loads analysis requirements?

26. What are the best approaches for ensuring an optimized design which properly trades between all disciplines?

27. How does the loads analyst ensure that no surprises occur during flight, etc.?

28. What is the proper blend between use of suppressors and isolators versus designing for maximum expected loads?

29. How does one ensure that the loads analysts are involved in design philosophy definitions?

30. What is proper balance between analysis and test in the verification phases?

Table 2 summarizes some general issues of the more general technology issues that arose from the Shuttle experience to date.

References 50 and 54 give excellent summaries of basic technology areas for structures. These are broader than loads but include loads. Since these are very concise articles, the summaries are not repeated here. Readers interested in more details should go to these articles.

Payload loads technology, in general, goes beyond the general technology items just listed. Here, the dynamics are a combination of low-frequency and high-frequency environments, generally classified as loads and as vibroacoustic criteria. In the past, the areas would be separated due to distinct frequency separation or boundaries. For Space Shuttle, this is not the case; the two overlap and must be treated together. This leads to several technology areas, namely:

1. Techniques for combining high- and low-frequency loads in a realistic, nonconservative manner.

2. Techniques for enveloping loads and accounting for uncertainties without undue weight penalties.

3. Analysis techniques that can calculate loads using only the payload model without all-up systems analysis.

4. Better means of estimating transmission loss across elements.

5. Improved techniques for analyzing components along the lines of statistical energy.

6. Optimize active and passive isolation techniques.

TABLE 2. TECHNOLOGY ISSUES.

- SHUTTLE EXPERIENCE TO DATE AND FUTURE PROGRAM CONCEPTS INDICATE STRONG NEEDS FOR:

  - JOINT AND INTERFACE MODELING TECHNOLOGY, INCLUDING NONLINEARITIES.
  - TRADE BETWEEN ACCURACY REQUIREMENTS, CONTROL COMPLEXITY, WEIGHT AND COST.
  - OPTIMIZED ANALYSIS TEST APPROACH

    - SCALE MODEL
    - MACRO ELEMENT
    - ON-ORBIT
    - ELEMENT

  - DEVELOPMENT OF EFFICIENT AND ACCURATE MODAL EXCITATION APPROACHES, DATA ACQUISITION/REDUCTION/EVALUATION, AND SELECTION CRITERIA.

- LOADS ARE A FUNCTION OF THE CONFIGURATION, GEOMETRY, MASS DISTRIBUTION, FORCE APPLICATION POINTS, LOAD PATHS, AND ENVIRONMENT LEADING TO THE FOLLOWING TECHNOLOGY AREAS:
  - DEVELOPMENT OF TECHNIQUES FOR GENERATING AERO DISTRIBUTIONS WITH VARIATIONS
  - ACCURATE DEFINITION OF ENVIRONMENTS (IGNITION OVERPRESSURE AND AERO).
  - DESIGN APPROACH THAT WILL SORT OUT CRITICAL DESIGN CASES REDUCING COMPUTER EVALUATION TIME.
  - CONFIGURATION DESIGN APPROACHES THAT PROPERLY TRADE OR OPTIMIZE BETWEEN MASS DISTRIBUTION, ENVIRONMENT, LOAD PATHS, ETC.
  - FLIGHT TEST AND GROUND TEST DATA ACQUISITION AND EVALUATION PROCEDURES THAT ALLOW ACCURATE EXTRACTION OF ENVIRONMENTS AND DYNAMIC CHARACTERISTICS.

- THIS SHUTTLE EXPERIENCE SHOWS THE NEED FOR RESEARCH THAT ESTABLISHES AN OPTIMIZED DESIGN APPROACH WHICH PROPERLY WEIGHS OR TRADES THE VARIOUS DISCIPLINES ASPECTS REQUIRED FOR LOW-COST HIGH-PERFORMANCE SPACE VEHICLES AND SPACE STRUCTURES.

  - DEVELOPMENT OF PERFORMANCE CRITERIA AND WEIGHT FACTORS.
  - OPTIMIZATION APPROACH THAT INCLUDES MANY DISCIPLINE PARAMETER INDICES.
  - UNCONSERVATIVE APPROACHES FOR HANDLING OR COMBINING SYSTEM TOLERANCES OR VARIATIONS WITH ENVIRONMENTS.
  - UNDERSTANDING OF THE PHENOMENON AND CRITICAL PARAMETERS REQUIRED TO ASSURE PROPER DESIGN.

- IDENTIFICATION OF A COMPREHENSIVE SET OF DESIGN CRITERIA AND ANALYSIS APPROACHES APPLICABLE FOR EACH TYPE OF SPACE VEHICLES.

  - ATTITUDE CONTROL STRUCTURAL/THERMAL INTERACTION
  - TEST, NO TEST
  - GEARED TO LOADS BOUNDARIES (HOW TO SET)